

Recent Results in Bottomonium Ties to Charmonium

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Recent results in studies of bottomonium especially relevant to charmonium are reviewed. This report covers dipion transition matrix elements, η production in Υ transitions, Υ decays to invisible particles, a search for a non-standard-model pseudoscalar Higgs in Υ radiative decays, and Υ radiative decays to $f_2(1270)$, η , and η' .

1. Introduction

In describing bottomonium results at a charm conference, we implicitly invoke heavy quark symmetry. The QCD is supposed to be the same, except that the bottom quark mass is about three times the charm quark mass, the magnitude of the electric charge is half as big, and the running strong coupling constant α_s is about 30% smaller. These differences will affect what portion of the effective potential is explored, how well the non-relativistic approximation works, decay multiplicities, and the number of bound quarkonium states, but the changes should, in principle, be calculable. This makes bottomonium a different laboratory to study the same physics as seen in charmonium. In this report, I will emphasize studies where bottomonium either extends, checks, or suggests new studies that can be done in charmonium.

Figure 1 compares the bound spectra of charmonium and bottomonium to illustrate some of these ideas. You can see that the bottomonium spectrum is richer, with more bound states and a wider variety of decay scenarios. It is also true that some of the fundamental states, including the ground state, have not yet been observed.

2. Relevant Experiments

The first Υ states were discovered in hadron collisions, and there is still interesting work being done in bottomonium at the colliders. In particular, D0 has recently measured polarization in hadroproduction of bottomonium. However, Jonas Rademacker discussed this in detail in his report [1], so I will not cover it here.

Direct production of bottomonia in e^+e^- collisions has been a fruitful method for studying their properties. CLEO has 6 million $\Upsilon(3S)$, 9 million $\Upsilon(2S)$, and 21 million $\Upsilon(1S)$ events. Belle collected 11 million $\Upsilon(3S)$. Of course, both Belle and BaBar have hundreds of millions of $\Upsilon(4S)$ events.

With so much luminosity, Belle and BaBar also produce tens of millions of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ events with initial state radiation, although these events are somewhat more difficult to use effectively.

3. Dipion Transition Matrix Element

For two decades, there has been a puzzle in the description of the dipion mass distribution in bottomonium decays, as illustrated in Fig. 2. While the dipion mass distribution for the charmonium transition $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$, and the two bottomonium transitions $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(2S)$ are well described by a single term in the matrix element [2], the transition $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ shows a more complicated, two hump structure. More recently, data from Belle [3] and Babar [4] shown in Fig. 3 add inputs to the puzzle, showing that the decay $\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ shows the simple behavior, while $\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(2S)$ is more complex.

CLEO has recently attempted to approach the problem by analyzing its Υ transition data in a two-dimensional Dalitz-like fitting procedure [5]. Brown and Cahn [6] describe the relevant matrix element using PCAC and current algebra in the general form

$$\begin{aligned} \mathcal{M} = & A(\epsilon' \cdot \epsilon)(q^2 - 2m_\pi^2) + \\ & B(\epsilon' \cdot \epsilon)E_1E_2 + \\ & C[(\epsilon' \cdot q_1)(\epsilon \cdot q_2) + (\epsilon \cdot q_1)(\epsilon' \cdot q_2)], \end{aligned} \quad (1)$$

where A , B , and C are complex parameters, ϵ and ϵ' are the Υ and Υ' polarization vectors, $q^2 = M_{\pi\pi}^2$, E_1 and E_2 are the pion energies, and q_1 and q_2 their four-momenta.

Instead of fitting in a single dimension $M_{\pi\pi}^2$, which is equivalent to allowing only the A term in the matrix element, CLEO fits in $M_{\pi\pi}^2 - M_{\Upsilon\pi}^2$ space. They assume that the complex-valued A , B , and C terms do not vary significantly over the phase space of any of the decays. In the fits they find that the C term is not needed, which is not unexpected because it involves flipping the spin of the heavy b quark. CLEO's limit is not very stringent, $|C/A| < 1.09\%$ at 90% confidence level, because the shapes of the C and B terms are very similar. If they set $C = 0$ they fit values for the ratio B/A given in Table I [5].

Dubynskiy and Voloshin [7] argue that the CLEO parametrization is too naïve because B cannot possibly be constant over the Dalitz plot. So CLEO's fits

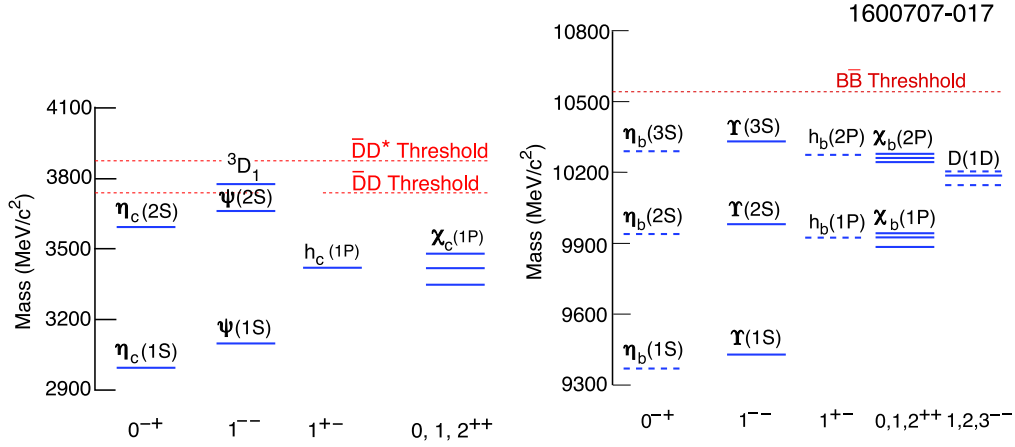


Figure 1: The spectra of bound charmonium and bottomonium. The vertical scales are the same, offset to align the ground states. States which have not yet been observed are rendered as dashed lines.

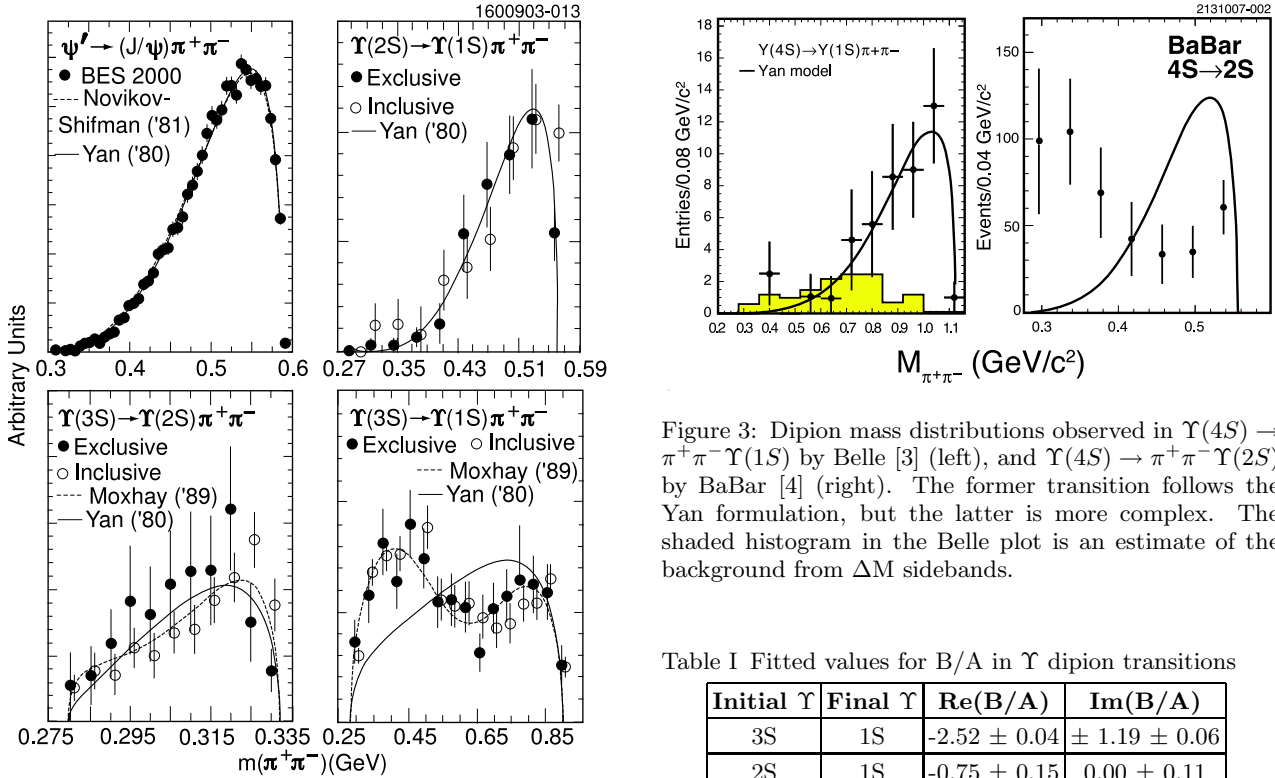


Figure 2: Dipion mass distribution in $\psi' \rightarrow \pi^+\pi^- J/\psi$ (upper left), $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ (upper right), $\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(2S)$ (lower left), and $\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ (lower right). All distributions are well described by the Yan[2] formulation, which keeps only the A term of Eq. 1, except the last which has a distinctly different shape.

are not universally recognized as a solution to the dipion transition puzzle. Yet they show the power of the Dalitz technique, and it would be useful for Belle in bottomonium and CLEO-c or BES in charmonium to see if this technique describes the data well.

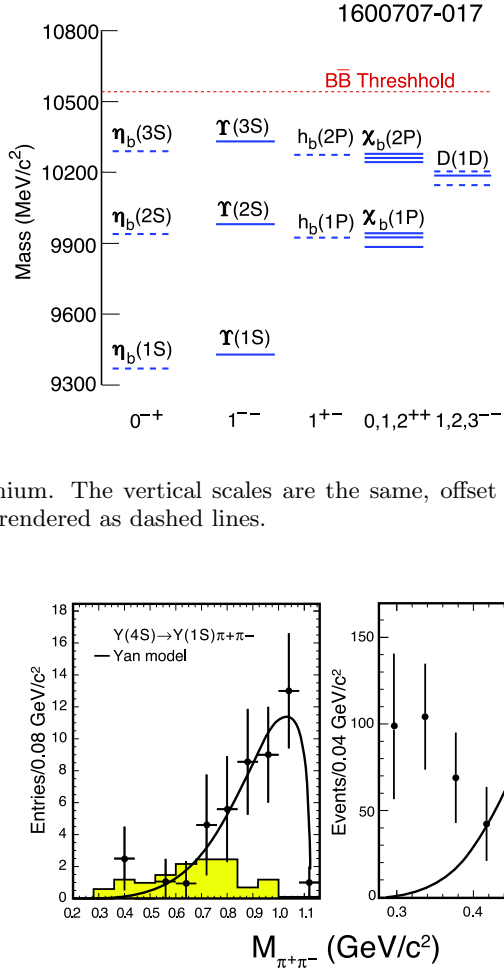


Figure 3: Dipion mass distributions observed in $\Upsilon(4S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ by Belle [3] (left), and $\Upsilon(4S) \rightarrow \pi^+\pi^- \Upsilon(2S)$ by BaBar [4] (right). The former transition follows the Yan formulation, but the latter is more complex. The shaded histogram in the Belle plot is an estimate of the background from ΔM sidebands.

Table I Fitted values for B/A in Υ dipion transitions

Initial Υ	Final Υ	$\text{Re}(B/A)$	$\text{Im}(B/A)$
3S	1S	-2.52 ± 0.04	$\pm 1.19 \pm 0.06$
2S	1S	-0.75 ± 0.15	0.00 ± 0.11
3S	2S	-0.40 ± 0.32	0.00 ± 1.10

4. Pseudoscalar Transitions

In the charmonium system $\psi(2S) \rightarrow \eta J/\psi$ is surprisingly large considering the small amount of available phase space, with about a 3% branching fraction [8]. Yan [2] predicted in 1980 that the rate in bottomonium should scale like $\Gamma \propto (p^*)^3/m_Q^4$. Kuang [9] has more recently refined this procedure and predicts $B(\Upsilon(2S) \rightarrow \eta \Upsilon(1S)) = (8.1 \pm 0.8) \times 10^{-4}$ and

$$B(\Upsilon(3S) \rightarrow \eta \Upsilon(1S)) = (6.7 \pm 0.7) \times 10^{-4}.$$

CLEO has sought $\Upsilon(2S) \rightarrow \eta \Upsilon(1S)$ in the final state where the Υ decays $\Upsilon(1S) \rightarrow \mu\mu$ or ee and the η decays $\eta \rightarrow \gamma\gamma$ or $\pi^+\pi^-\pi^0$.

CLEO plots the yield as a function of the kinetic energy of the η candidate. In this preliminary analysis CLEO sees a 5 standard deviation peak in the kinetic energy of the $\gamma\gamma$ from η decay as shown in Fig. 4. This leads to a (preliminary) branching fraction of $B(\Upsilon(2S) \rightarrow \eta \Upsilon(1S)) = (2.5 \pm 0.7 \pm 0.5) \times 10^{-4}$, somewhat smaller but in the same general range as Kuang's prediction. CLEO also sees three events, with nearly zero expected background, in the η decay channel $\eta \rightarrow \pi^+\pi^-\pi^0$, which corresponds to a consistent branching fraction.

Using the same technique, CLEO also seeks $\Upsilon(2S) \rightarrow \pi^0 \Upsilon(1S)$, but sees no significant excess over background, setting the (preliminary) 90% confidence level upper limit $B(\Upsilon(2S) \rightarrow \pi^0 \Upsilon(1S)) < 2.1 \times 10^{-4}$. This is consistent with the expectation, obtained using Yan's simple scaling prediction, that the π^0 rate should be 0.16 of the η rate.

5. $\Upsilon(1S)$ Decays to Invisible Particles

The decays of charmonium or bottomonium states to undetectable particles are a window on physics beyond the Standard Model. McElrath [10] has predicted that the neutralino χ , a dark matter candidate, could be produced in $\Upsilon(1S) \rightarrow \chi\chi$ with a branching fraction of 0.41%. Possible production of new gauge bosons or a light gravitino was described by Fayet [11]. While it is true that $\Upsilon(1S) \rightarrow \nu\nu$ via Z^0 production is a potential background, it is calculated to be tiny enough as not to present a problem.

But how can you “see” these invisible decays? The trick is to produce a higher Υ state which decays via a two-pion transition to the $\Upsilon(1S)$. The experimentalist then uses the two pions to both trigger the detector and to signal the presence of the $\Upsilon(1S)$ with the missing mass recoiling against the dipion. The remainder of the detector must be completely empty.

Figures 5 and 6 show the results of two searches. Belle [12] uses $\Upsilon(3S)$ events so the transition pions have enough energy to trigger the detector reliably. The top of Fig. 5 shows the dipion mass spectrum when the $\Upsilon(1S) \rightarrow \mu\mu$ decay is observed, to demonstrate the expected shape of a possible signal. The bottom part of the figure shows the dipion mass spectrum when the rest of the detector shows no tracks and less than 3 GeV of neutral energy.

The CLEO data sample consists of 9 million $\Upsilon(2S)$ decays, almost as large as Belle's 11 million $\Upsilon(3S)$ decays, and with the advantage of a more favorable dipion branching rate to $\Upsilon(1S)$. Unfortunately, their two track trigger had to be prescaled by a factor 20 to prevent saturating the data acquisition system. CLEO's

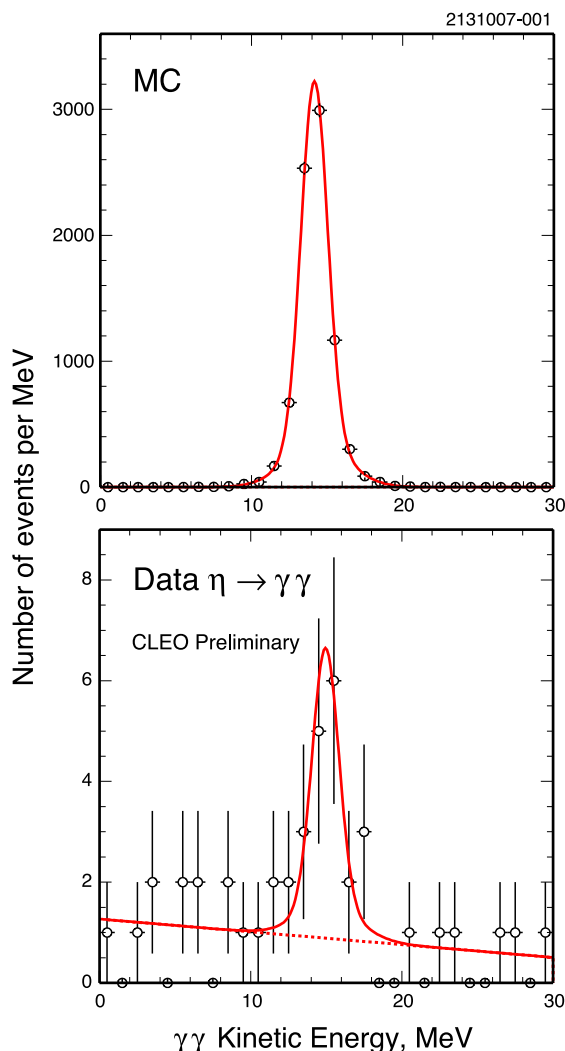


Figure 4: The predicted and observed signal for η production in $\Upsilon(2S) \rightarrow \eta \Upsilon(1S), \eta \rightarrow \gamma\gamma$.

results [13] are shown in Fig. 6. The top half shows the inclusive dipion mass spectrum, and the bottom half shows what remains when the rest of the detector is required to show no tracks and no photons of energy more than 250 MeV.

A small peak is visible at the $\Upsilon(1S)$ mass in the bottom parts of both figures. In both cases, the observed peaking is consistent with what is expected from Monte Carlo simulations where the decay products of the Υ traveled down the beam line, thus escaping the detector. Both experiments thus set upper limits to the production of invisible particles in $\Upsilon(1S)$ decays

$$B(\Upsilon(1S) \rightarrow \text{“invisible”}) < 0.25\% \text{ (Belle)}, \text{ and } B(\Upsilon(1S) \rightarrow \text{“invisible”}) < 0.39\% \text{ (CLEO)}.$$

Each of these limits is an order of magnitude better than the previous best limit. Together, they set a limit on the branching fraction about half the McElrath prediction for neutralino production, and better

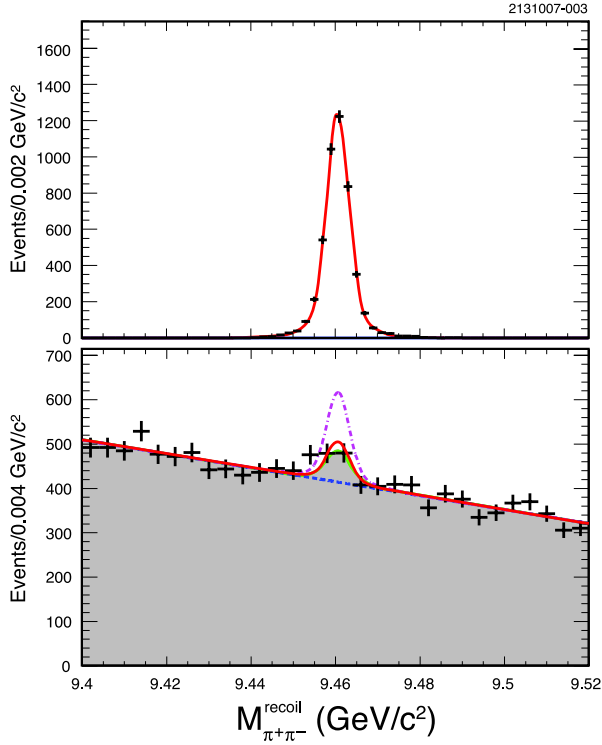


Figure 5: The results of Belle's search for the decay sequence $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \rightarrow$ "invisible." The top panel shows the $\pi\pi$ invariant mass when $\Upsilon(1S) \rightarrow \mu\mu$, and the bottom panel shows when the two pions and nothing more are seen in the detector. The peak seen in the lower plot is consistent with expected backgrounds (grey).

the previous gravitino mass limit by a factor of four, to $m_{3/2} > 1.2 \times 10^{-7}$ eV.

Similar searches to these can be performed in the charmonium system, where a much larger number of ψ' events is available. Of course, the mass range that can be explored is more limited, and the predicted branching fractions tend to be smaller, but such searches might be fruitful for charmonium experiments to pursue.

6. Radiative Decays of $\Upsilon(1S)$

6.1. Higgs Search

In an effort to explain why the Higgs hasn't yet been seen, Dermisek, Gunion, and McElrath [14] propose adding a non-Standard-Model-like pseudoscalar Higgs a_0 to the Minimal Supersymmetric Standard Model (MSSM) to make it the "Nearly MSSM" (NMSSM). This a_0 must have mass less than twice the b quark mass, so that it can't decay to a pair of b quark jets. This proposal explains the failure of the LEP experiments to see the Higgs at masses up to 100 GeV, since the daughters of the Higgs decay can't make the

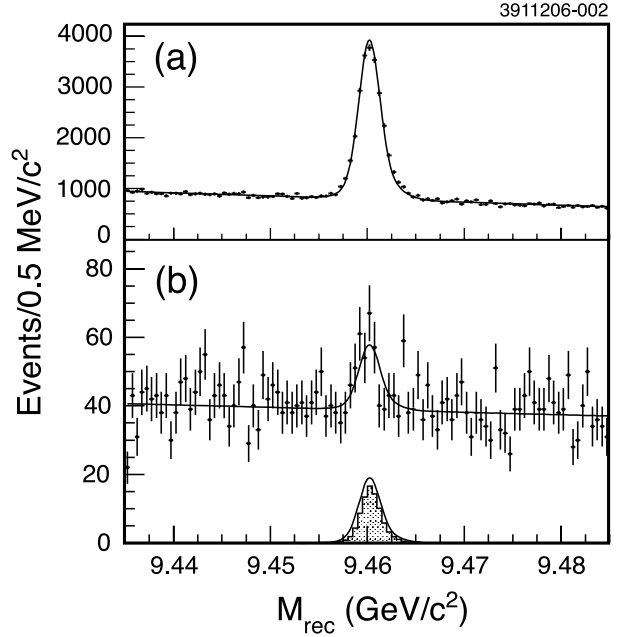


Figure 6: The results of CLEO's search for the decay sequence $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \rightarrow$ "invisible." The top panel shows the $\pi\pi$ invariant mass in all $\Upsilon(2S)$ decays and the bottom panel shows when the two pions and nothing more are seen in the detector. The shaded histogram at the bottom of the figure represents the expected background and is consistent with what is observed.

b jets those experiments sought. Yet the hypothesis is natural, in the sense that it avoids fine tuning of parameters to explain observations.

The a_0 should decay predominantly into $\tau\tau$ if it has enough mass, and should be observable in $\Upsilon(1S) \rightarrow \gamma a_0$.

CLEO has sought these new Higgses by looking for monochromatic photons in events likely to contain taus. They tag $\Upsilon(1S)$ from $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ to help eliminate the copious QED backgrounds from $e^+e^- \rightarrow \gamma\tau\tau$. They flag the presence of τ pairs by seeking two 1-prong τ decays, one of which must be to a lepton, and by demanding missing energy in the event. The spectrum of photons they observe in such events is shown in Fig. 7, and leads to upper limits shown in Fig. 8. These upper limits improve on older measurements by an order of magnitude or more, and rule out much of the parameter space for NMSSM models.

6.2. $\Upsilon(1S) \rightarrow \gamma f_2(1270)$

In the charmonium system, radiative decays are common and many have been observed. The decay $J/\psi \rightarrow \gamma f_2(1270)$ is one of the most common. In bottomonium, few exclusive radiative decays are measured, but now CLEO has observed [15] $\Upsilon(1S) \rightarrow$

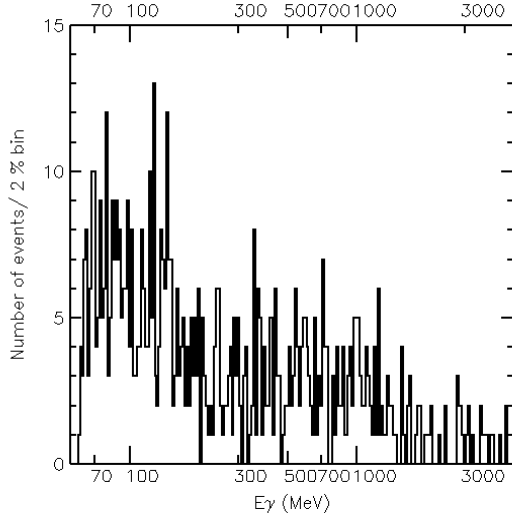


Figure 7: The spectrum of photons in τ -enriched $\Upsilon(1S)$ decays observed at CLEO.

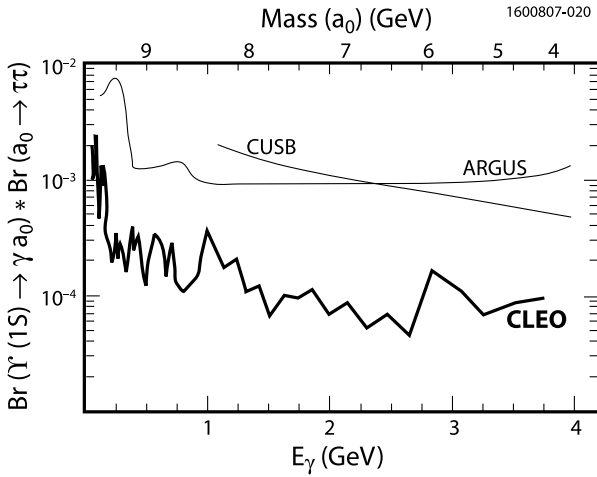


Figure 8: Upper limits on the branching fraction of $\Upsilon(1S) \rightarrow \gamma a_0$ vs. photon energy (bottom scale) and a_0 mass (top scale).

$\gamma f_2(1270)$ as can be seen in Fig. 9.

We test the simple heavy quark symmetry relation

$$B(J/\psi \rightarrow \gamma f_2)/B(\Upsilon(1S) \rightarrow \gamma f_2) = (q_c/q_b)^2 (m_b/m_c)^2 (\Gamma_{bb}/\Gamma_{cc}) \approx 20$$

using the CLEO observations [15]

$$B(\Upsilon(1S) \rightarrow \gamma f_2) = (10.2 \pm 0.8 \pm 0.7) \times 10^{-5} (\pi^+ \pi^-)$$

$$B(\Upsilon(1S) \rightarrow \gamma f_2) = (10.5 \pm 1.6 \pm 1.9) \times 10^{-5} (\pi^0 \pi^0)$$

$$B(\Upsilon(1S) \rightarrow \gamma f_2) = (10.23 \pm 0.97) \times 10^{-5} \text{ (combined).}$$

The observed ratio

$$B(J/\psi \rightarrow \gamma f_2)/B(\Upsilon(1S) \rightarrow \gamma f_2) = 14.0 \pm 1.7$$

is in satisfactory agreement with the expectations from scaling.

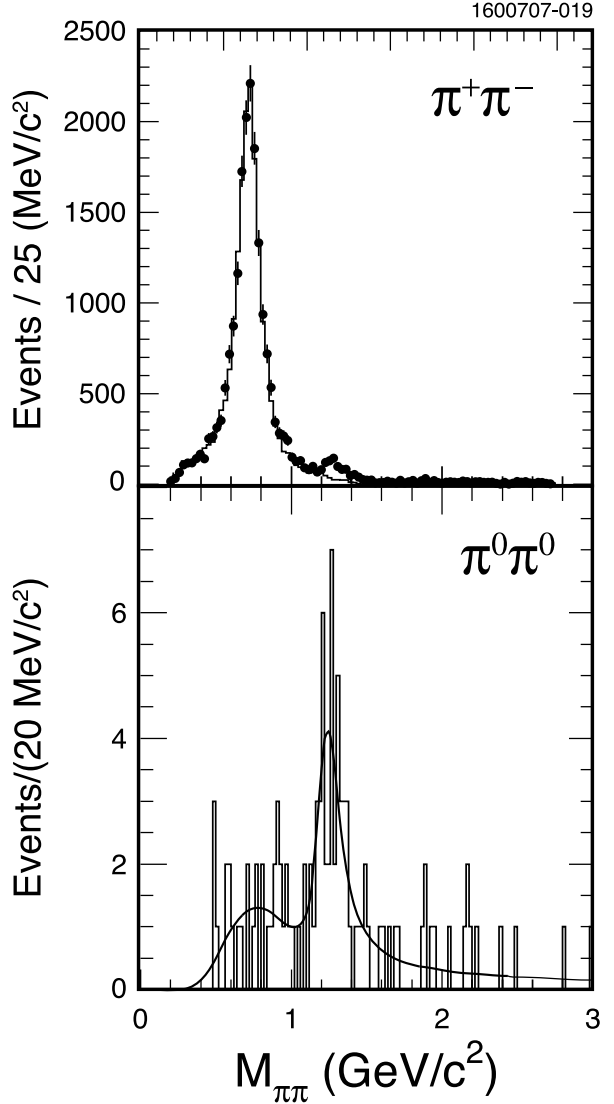


Figure 9: CLEO observes $\Upsilon(1S) \rightarrow \gamma f_2(1270)$ with the f_2 decaying to charged pions (top) and neutral pions (bottom). The charged pion signal is contaminated with a huge background from $e^+e^- \rightarrow \gamma \rho$, but the observed small signal is confirmed in the neutral pion channel.

6.3. $\Upsilon(1S) \rightarrow \gamma \eta'$ and $\gamma \eta$

Does this success of scaling in radiative decay to f_2 carry over to other radiative decays? Another prominent decay in the charmonium system is $B(J/\psi \rightarrow \gamma \eta') = (4.7 \pm 0.3) \times 10^{-3}$ [8]. Using the observed charmonium system decay rate ratio $B(J/\psi \rightarrow \gamma \eta')/B(J/\psi \rightarrow \gamma f_2) = (3.4 \pm 0.4)$, and the relative rates of Υ and J/ψ to f_2 , we can predict the radiative decay rates for $\Upsilon(1S)$ to η and η' . The expectation is that these decays should be easily visible.

We already know that η' is unconventional. In radiative J/ψ decay its branching fraction is five times as large as that for η . There have been speculations

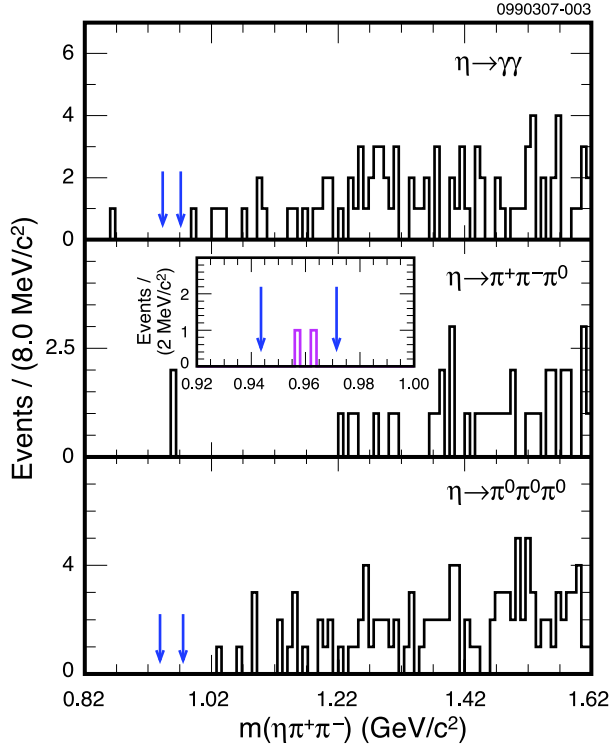


Figure 10: CLEO seeks $\Upsilon(1S) \rightarrow \gamma\eta'$ with the η' decaying to $\pi^+\pi^-\eta$ and the daughter η decaying in any of three modes. The blue arrows indicate where an expected η' signal should be visible. Two candidates are seen in the mode where $\eta \rightarrow \pi^+\pi^-\pi^0$, but none are visible in the two all-neutral η decay modes, leading to the upper limit quoted in the text.

that it might contain sizable gluon content [16], or possible charmonium content. Theorists have used the vector dominance model (VDM) [17], η_b mixing [18], or higher twist to try to understand the unusual behavior of the η' .

CLEO has sought radiative decays to η' and η in 21 million $\Upsilon(1S)$ decays with the η' results shown in Fig. 10. The upper limits they set are significantly more stringent than former measurements, $B(\Upsilon(1S) \rightarrow \gamma\eta') < 1.9 \times 10^{-6}$ and $B(\Upsilon(1S) \rightarrow \gamma\eta) < 1.0 \times 10^{-6}$, whereas naïve scaling as outlined above predicts 350×10^{-6} and 70×10^{-6} , respectively. So naïve scaling fails here by two orders of magnitude.

These upper limits contradict the mixing approach of Chao [18] by a factor of 30, but are still above the VDM predictions of Intemann [17] and the higher-twist description of Ma [19].

7. Conclusion

Bottomonium remains an active field of research at Fermilab, CLEO, Belle and Babar. I have presented

new results in dipion transitions among Υ states, η and π^0 transitions in the Υ system, searches for invisible particles and a new type of Higgs, and radiative transitions to $f_2(1270)$, η , and η' . However, bottomonium studies are continuing, and more new results can be expected next year.

Acknowledgments

Richard Galik was in the midst of preparing this talk when external circumstances forced him to turn it over to me. He had already chosen most of the topics, prepared a few of the slides, and done much of the research that went into the preparation of this note. I want to thank him for that work and the many helpful consultations we had.

This work was supported by the National Science Foundation under contract NSF PHY-0202078.

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